The Contribution of *Dreissena* to the Resurgence of *Cladophora* in eastern Lake Erie.

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Introduction

From 1995 to 2003 widespread *Cladophora* blooms were documented along the rocky coastlines of eastern Lake Erie (Higgins et al. in press). *Cladophora* blooms have also been recently reported in Lake Ontario (T. Howell Ontario Ministry of the Environment, pers. com., Hiriart-Baer et al. submitted, S. Malkin, University of Waterloo, unpublished data), Lake Michigan (Byappanahalli et al. 2003; H. Bootsma, this report), and portions of Lake Huron (T. Howell, pers. com.). The presence of widespread algal blooms in the coastal zones of these lakes (or lake basins), all of which are considered oligotrophic by offshore total phosphorus concentrations, are highly troublesome and may be a symptom of fundamental shifts in water quality caused by the invasive Zebra and Quagga mussels (*Dreissena polymorpha* and *D. bugensis* respectively).

Cladophora blooms were a significant ecological phenomenon in these Laurentian Great Lakes during the 1960's through to the early 1980's (Bellis and McClarty 1967; Herbst 1969; Shear and Konasewich 1975; Auer et al. 1982; Millner and Sweeney 1982). During the late 1970's a significant modeling effort to understand the dynamics of *Cladophora* growth and biomass accrual resulted in the development of a mathematical growth model specific to *Cladophora* (Auer and Canale 1980; Auer et al. 1982; Canale and Auer 1982a, b; Auer and Canale 1982a, b; Graham et al. 1982). The *Cladophora* growth model (subsequently referred to as the 'Canale and Auer' model), which relates growth and biomass accrual to several dynamic parameters including light, temperature, dissolved phosphorus, and carrying capacity was successfully validated on field populations of *Cladophora* in proximity to a sewage treatment outfall in Lake Huron (Canale and Auer 1982b). Recently, the 'Canale and Auer' model was revised, brought into a user-friendly computer-modeling platform (Stella) and successfully validated on field populations of *Cladophora* in eastern Lake Erie (Higgins et al. submitted).

The revised 'Canale and Auer' model is used here to determine the relative importance of highly variable ecological data to the current growth and biomass accrual in eastern Lake Erie, to demonstrate the contribution of *Dreissena* induced changes in water quality to the resurgence of *Cladophora*, and to provide necessary information for the management of *Cladophora* in eastern Lake Erie.

Methods
Site Description

Approximately 77% of the northern shoreline of Lake Erie's eastern basin consists of bedrock and cobble lake bottoms of low slope (Rukavina and St. Jacques 1971; St. Jacques and Rukavina 1973). During 1995, 16 sites were sampled for *Cladophora* community characteristics, tissue nutrient status, and biomass once during the peak growing season (Howell 1998). During 2001 and 2002 an additional 8 sites were added, and five of these sites were chosen for intensive seasonal studies of *Cladophora* and water quality parameters required for modeling purposes. All sites chosen had hard rocky lake bottoms that were colonized by *Dreissena*. Current mean *Dreissena* densities in the littoral zone of eastern Lake Erie range from 4,000 – 11,000 ind./m^2 (Patterson et al. submitted).

Field Observations/Collections

Field observations and collections were conducted by snorkeling or SCUBA. At each site at least 3 quadrats (0.5m x 0.5m) were sampled using an airlifting devise described by Barton and Hynes (1978). The collection of meteorological data and water quality data for modeling purposes is described in detail elsewhere (Higgins et al. submitted; Higgins et al. in press).

Results and Discussion

Current Status

The mean peak biomass of *Cladophora* during 1995, 2001, and 2002 was similar to historical values in the eastern and western basins of Lake Erie (Figure x) during the 1960's and 1970's, a period where the International Joint Commission (IJC) declared *Cladophora* a 'serious problem' to the lower Laurentian Great Lakes (Shear and Konansewich 1975). Unfortunately, very little data exists for *Cladophora* biomass in eastern Lake Erie during the 1980's, a period where total phosphorus concentrations were greatly reduced, but prior to the invasion of the Dreissenid mussels. In Lake Ontario, tissue P concentrations and *Cladophora* biomass were reduced through the mid-1980's (Painter and Kamaitis 1987), and it is likely that *Cladophora* growth and bloom formation in Lake Erie was also reduced.

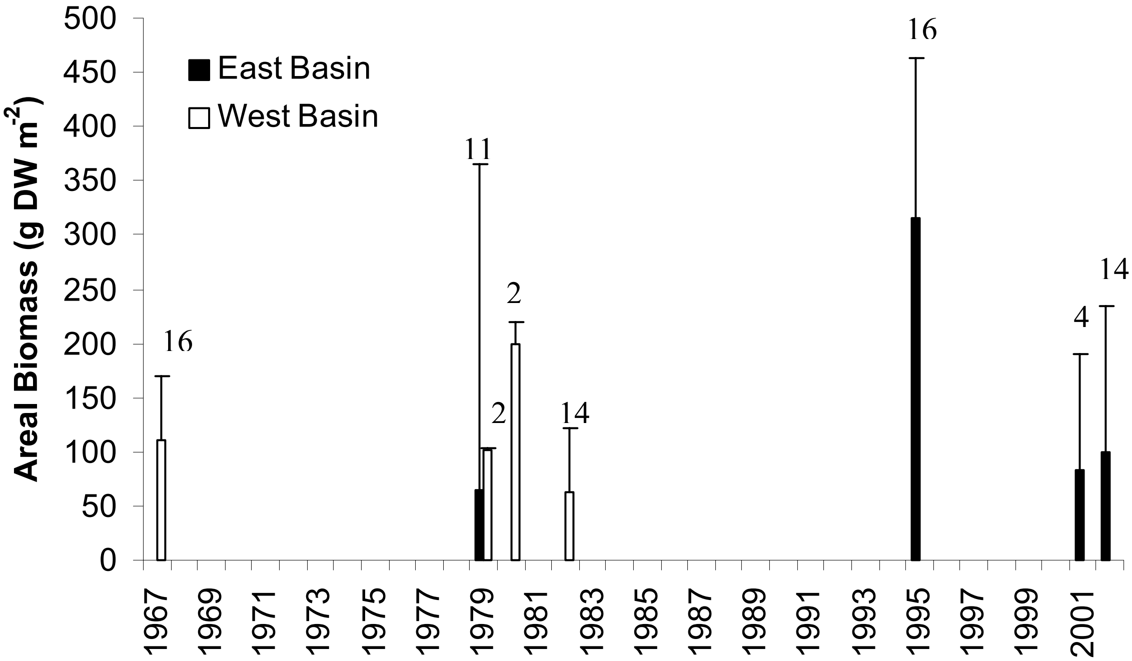

Figure 1. *Cladophora* biomass at shallow depths (<3m) during the peak biomass period in Lake Erie. Methods of collection differ between years. Pre-1995 data from Mantai et al. 1982, Neil and Jackson 1982, Kishler in Taft 1975, Lorenz and Herdendorf 1982, Monaco 1985. Data from 1995 from Howell et al. 1998. Data from 2001 and 2002 from Higgins et al. in press. The number above each bar represents the number of sites sampled and averaged.

Factors controlling growth and biomass

Although many factors are required for *Cladophora* growth, several factors have been identified as being most important to controlling both the growth rates and biomass accrual of *Cladophora* in the Laurentian Great Lakes. In eastern Lake Erie *Cladophora* blooms are a common feature of the northern shoreline, and the median areal coverage over suitable substrata is approximately 96% at depths less than 5m. From 1995 to 2002 the northern shoreline of Lake Erie's eastern basin supported a maximum standing crop of approximately 12,000 tonnes dry mass (DM) of *Cladophora*. Presumably, if more suitable substratum were available the total standing crop would also increase.

The mean standing crop of *Cladophora* over depth is strongly correlated with the availability of light (Figure 2). At shallow depths, where irradiance is highest, small variations in irradiance have little effect on the standing crop. At these shallow depths (<3m) *Cladophora* growth and biomass accrual is limited by factors other than the quantity of light. At deeper depths (>3m) light becomes increasingly important to controlling growth rates and small variations in irradiance have large effects on the standing crop (Figure 2).

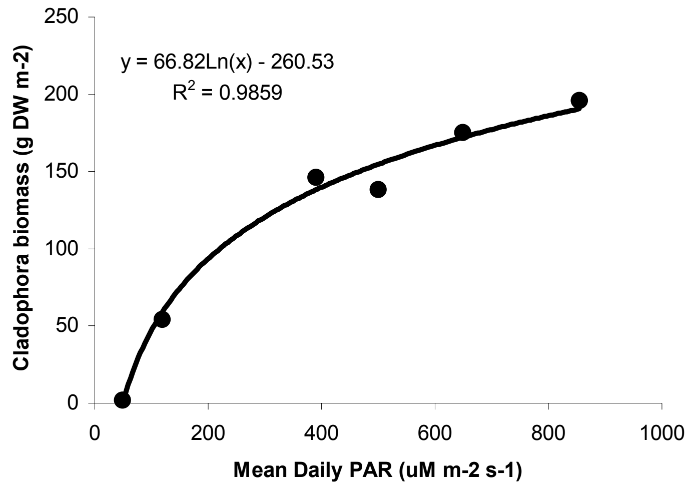

Figure 2. *Cladophora* biomass in eastern Lake Erie as a function of mean daily PAR. *Cladophora* biomass values are from Table 1. Mean daily PAR calculated from mean daytime surface irradiance and water column transparency during the spring growth period (see Higgins et al. in press for calculations).

The growth rates and maximum biomass accrual of *Cladophora* at shallow depths in eastern Lake Erie are strongly phosphorus limited (Higgins et al. in press). The relationship between tissue P concentrations and maximum growth rates has been determined for *Cladophora* using the Droop model (Auer and Canale 1982b). The Droop model illustrates that during the peak biomass period, maximum growth rates were strongly controlled by tissue phosphorus concentrations at depths shallower than 5m (Figure 3). At depths greater than 5m, tissue P concentrations were higher and maximum growth rates became increasingly insensitive to small shifts in tissue P. Seasonally, the tissue P concentration declined from 0.25 % DM during late May 2002 to values approaching 0.06 % DM by late June 2002 (Higgins et al. in press). The decline in tissue P concentrations over this period corresponds to a decrease in lake wide SRP concentrations (Higgins et al. in press). The decline in tissue P during this period indicates that SRP from *Dreissena* and other sources was insufficient to maintain high tissue P concentrations and maximal growth rates.

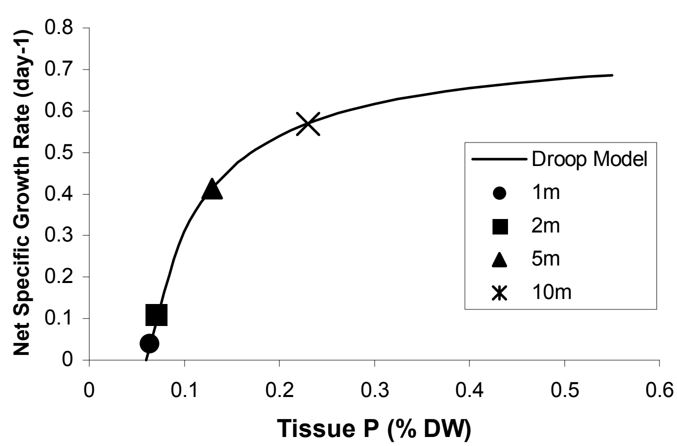

Figure 3. The relationship between tissue phosphorus concentrations and net specific growth in *Cladophora* as predicted by the Droop equation (Auer and Canale 1982). Tissue P data from eastern Lake Erie from the early summer period (July).

In order to confirm P limitation in *Cladophora* tissues an *in situ* P addition experiment was performed using P-enriched and non-P enriched agar. While the experiment was fraught with methodological problems, the effects of P enrichment were clearly noted in several trials. In these successful trials, *Cladophora* that received the P treatment overgrew the sampling container and were bright green in colour, while *Cladophora* in the non-P treatment showed stunted growth and appeared an unhealthy dull green colour.

In addition to other factors, the growth rates and seasonality of *Cladophora* are mediated by temperature (Graham et al. 1982). In eastern Lake Erie visible growths of *Cladophora* were noted as water temperatures approached 10 C, and maximum accumulation of biomass occurred as temperatures approached 20 C. In 2002 the midsummer-sloughing event occurred as temperatures approached 23.5 C.

Modeling growth and biomass

The ‘Canale and Auer’ model provides an excellent framework for understanding the complex interactions of highly dynamic ecological variables that control growth rates and biomass accrual. The revised model can also be used to estimate how changes in single or multiple model parameters (e.g. surface irradiance, water clarity, temperature, dissolved phosphorus) affect growth rates. For eastern Lake Erie the model was used to evaluate the contribution of *Dreissena* to the resurgence of *Cladophora*, and how current shifts in SRP concentration would affect depth integrated biomass. The modeling effort indicated, based on shifts in water clarity (Howell et al. 1995) and spring SRP concentrations (Makarewicz et al. 2000) that occurred over *Dreissena* invasion, that *Dreissena* induced changes in water quality were responsible for increasing basin wide *Cladophora* biomass from approximately 3,000 tonnes DM (pre-*Dreissena*) to 12,000 tonnes DM (post-*Dreissena*)(Figure 5). Under current post-*Dreissena* conditions, the model indicated that depth-integrated biomass was highly sensitive to increases or decreases in ambient dissolved phosphorus concentrations.

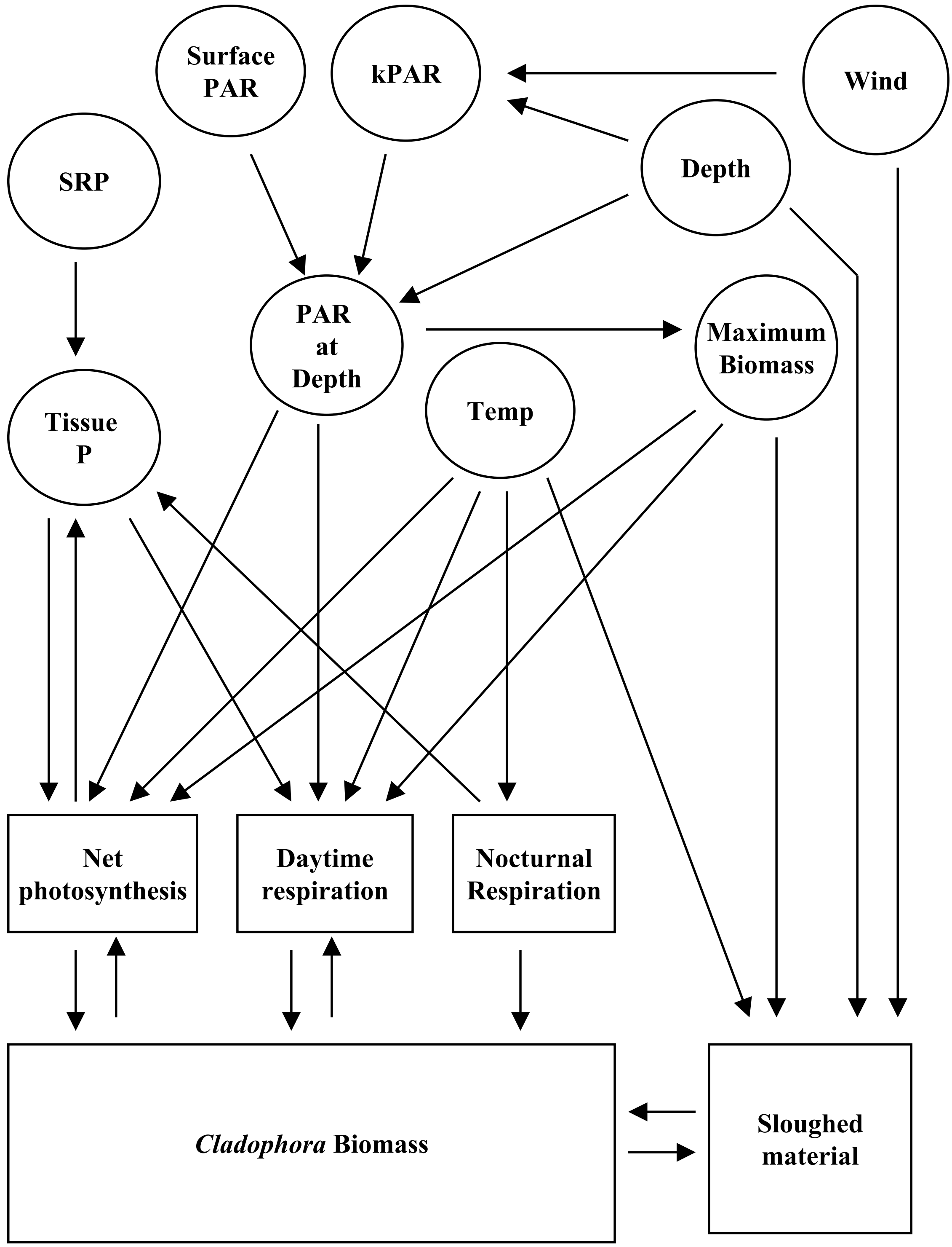

Figure 4. Simplified diagram of the revised *Cladophora* growth model (Higgins et al. submitted). Arrows represent mathematical equations linking model parameters.

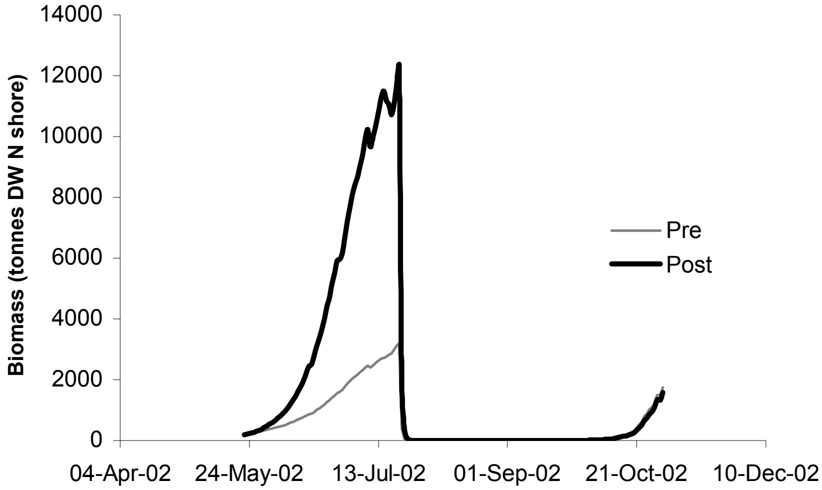

Figure 5. Model simulated depth-integrated *Cladophora* biomass on the northern shoreline of Lake Erie's eastern basin pre and post-*Dreissena* invasion. Post *Dreissena* conditions are based on data collected during 2002 by Higgins et al. (submitted). Pre-*Dreissena* model simulations are based on SRP concentrations (Makarewicz et al. 2000) and water clarity (Howell 1998) immediately prior to *Dreissena* invasion while holding other input parameters identical to post-*Dreissena* values.

Conclusion

The 'Canale and Auer' model provides an excellent framework for understanding the interactions of highly dynamic ecological variables that control growth rates and biomass accrual of *Cladophora*. The 'Canale and Auer' model was revised, brought into a user-friendly computer modeling platform (Stella 2001), successfully validated in eastern Lake Erie (Higgins et al. submitted), and used to estimate the contribution of *Dreissena* to the resurgence of *Cladophora* and to determine how *Cladophora* would respond to shift in dissolved P concentrations. Under current post-*Dreissena* conditions in eastern Lake Erie, depth integrated *Cladophora* biomass is highly sensitive to dissolved phosphorus and small increases or decreases can have dramatic effects on basin wide *Cladophora* production. Phosphorus released by *Dreissena* was insufficient to meet *Cladophora* growth requirements on short time scales. Increased spring SRP concentrations due to *Dreissena*, however, appeared to be the main cause of the dramatic resurgence of *Cladophora* and the widespread bloom formations across the northern shoreline.

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